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Electromagnetic device

FIELD OF THE INVENTION AND PRIOR ART

This invention is related to an electromagnetic device comprising at least one magnetic circuit and at least one electric circuit comprising at least one winding, the magnetic and electric circuits being inductively connected to each other and the device comprising a control arrangement to control operation of the device.

This electromagnetic device may be used in any electrotechnical connection. The power range may be from VA up to the 1000-MVA range. High voltage applications are primarily intended, up to the highest transmission voltages used today.

According to a first aspect of the invention a rotating electric machine is contemplated. Such electric machines comprise synchronous machines which are mainly used as generators for connection to distribution and transmission networks, commonly referred to below as power networks. The synchronous machines are also used as motors and for phase compensation and voltage control, in that case as mechanically idling machines. The technical field also comprises double-fed machines, asynchronous converter cascades, external pole machines, synchronous flux machines and asynchronous machines.

According to another aspect of the invention, said electromagnetic device is formed by a power transformer or reactor. For all transmission and distribution of electric energy, transformers are used and their task is to allow exchange of electric energy be-

tween two or more electric systems and for this, electromagnetic induction is utilized in a well-known manner. The transformers primarily intended with the present invention belong to the so-called power transformers with a rated power of from a few hundred kVA up to more than 1000 MVA with a rated voltage of from 3-4 kV and up to very high transmission voltages, 400 kV to 800 kV or higher.

Although the following description of the prior art with respect to the second aspect mainly refers to power transformers, the present invention is also applicable to reactors, both single-phase and three-phase reactors. As regards insulation and cooling there are, in principle, the same embodiments as for transformers. Thus, air-insulated and oil-insulated, self-cooled, pressure-oil cooled, etc., reactors are available. Although reactors have one winding (per phase) and may be designed both with and without a magnetic core, the description of the background art is to a large extent relevant also to reactors.

The at least one winding of the electric circuit may in some embodiments be air-wound but comprises as a rule a magnetic core of laminated, normal or oriented, sheet or other, for example amorphous or powder-based, material, or any other action for the purpose of allowing an alternating flux, and a winding. The circuit often comprises some kind of cooling system etc. In the case of a rotating electric machine, the winding may be disposed in the stator or the rotor of the machine, or in both.

A problem with known embodiments of electromagnetical devices of the above indicated nature is that it is either relatively difficult to achieve efficient control within a certain spectrum of parameters or that the control arrangements tend to be relatively costly. It is in this connection pointed out that it is known within the generator art to execute control of operation parameters via the field winding. If the rotor comprises electro-

magnets, this field winding is provided on the rotor with the disadvantages this involves in the form of a more expensive and more difficult-to-control embodiment. In the case of a permanent magnet rotor, the problem arises that field control is not practically possible. This makes it, of course, more difficult to carry out control in general and in especially delicate control situations in particular. A further problem with prior art is that the conventional winding technique makes it expensive to obtain the windings. The known embodiments also cause substantial energy losses and involve restrictions as far as the location of the windings in the magnetic circuit is concerned.

SUMMARY OF THE INVENTION

The object of the present invention is to devise ways to simplify and improve the possibilities to control operation of electromagnetic devices according to the precharacterizing part of the enclosed claim 1, better conditions for rational winding production and mounting also being aimed at.

The basic object of the present invention is achieved by arranging the control arrangement to control frequency, amplitude and/or phase with respect to electric power to/from the device by the control arrangement comprising means to control the magnetic flux in the magnetic circuit.

Thus, the present invention is based upon the idea to directly affect, by flux control, the magnetic flux in the magnetic circuit in a desired regard so as to be able to control the operation of the device. This provides a very rational and cost efficient embodiment, and besides increased possibilities to control so as to achieve an optimized operation.

According to a particularly preferred embodiment of the invention, the control means comprises at least one control winding

inductively connected to the magnetic circuit. The control arrangement is, accordingly, capable of effecting, via the control winding, required control of the magnetic flux in the magnetic circuit by applying, via the control winding, such control parameters that the magnetic flux in the magnetic circuit is affected in the required extent. The control winding could even be short-circuited. The magnetic flux may then in certain embodiments not pass the control winding. Depending upon the design of the magnetic circuit, partial or total blocking of the magnetic flux may occur.

Examples of control functions which may be achieved with the solution according to the invention are voltage change and voltage stabilization, elimination of transients, damping of oscillations in the power network, filtering-off of overtones, frequency adjustments and phase adjustments (in case separate control for the phases is provided for). It is pointed out that the control arrangement according to the invention may be adapted to add a magnetic flux addition to the magnetic flux in the magnetic circuit, i.e. the control arrangement could operate with direct energy supply.

The control according to the invention of the magnetic flux in the magnetic circuit means, for instance in a transformer, that a good control can be executed over the secondary winding voltage so that it fulfils the requirements imposed despite troublesome fluctuations regarding the primary voltage or the load connected to the secondary winding.

Further details and advantages with the flux control according to the invention in the magnetic circuit will appear from the following detailed description.

It is within the scope of the invention that at least one of the windings of the electromagnetic device or at least a part of this

winding comprises at least one flexible electrical conductor having a casing, which is magnetically permeable but capable of substantially enclosing the electric field occurring around the conductor. Expressed in other words, this means that the flexible electrical conductor and the casing thereof (in the form of an insulation system) are formed by means of a flexible cable. This involves substantial advantages with respect to manufacturing and mounting compared to the rigid windings in prefabricated shape which have been conventional up to now. The insulation system according to the invention results, in addition, in absence of gaseous and liquid insulation materials.

Since the electric field occurring about the electric conductor in the cable in the invention is substantially enclosed in the insulation system, the invention reduces occurring losses such that the device accordingly may operate with a higher degree of efficiency. The reduction of losses results, in its turn, in a lower temperature in the device, which reduces the need for cooling and allows possibly occurring cooling devices to be designed in a more simple way than without this aspect of the invention.

As to the aspect of the invention as a rotating electric machine it is thus possible to operate the machine with such a high voltage that the conventional step-up transformers can be omitted. That is, the machine can be operated with a considerably higher voltage than machines according to the state of the art to be able to perform direct connection to power networks. This means considerably lower investment costs for systems with a rotating electric machine and the total efficiency of the system can be increased. The invention eliminates the need for particular field control measures at certain areas of the winding, such field control measures having been necessary according to the prior art. A further advantage is that the invention makes it more simple to obtain under- and overmagnetization for the purpose of reducing

reactive effects as a result of voltage and current being out of phase with each other.

As to the aspect of the invention as a power transformer/ reactor, the invention, first of all, eliminates the need for oil filling of the power transformers and the problems and disadvantages associated thereto.

The design of the winding so that it comprises, along at least a part of its length, an insulation formed by a solid insulating material, inwardly of this insulation an inner layer and outwardly of the insulation an outer layer with these layers made of a semi conducting material makes it possible to enclose the electric field in the entire device within the winding. The term "solid insulating material" used herein means that the winding is to lack liquid or gaseous insulation, for instance in the form of oil. Instead the insulation is intended to be formed by a polymeric material. Also the inner and outer layers are formed by a polymeric material, though a semiconducting such.

The inner layer and the solid insulation are rigidly connected to each other over substantially the entire interface. Also the outer layer and the solid insulation are rigidly connected to each other over substantially the entire interface therebetween. The inner layer operates equalizing with respect to potential and, accordingly, equalizing with respect to the electrical field outwardly of the inner layer as a consequence of the semiconducting properties thereof. The outer layer is also intended to be made of a semiconducting material and it has at least an electrical conductivity being higher than that of the insulation so as to cause the outer layer, by connection to earth or otherwise a relatively low potential, to function equalizing with regard to potential and to substantially enclose the electrical field resulting due to said electrical conductor inwardly of the outer layer. On the other

hand, the outer layer should have a resistivity which is sufficient to minimize electrical losses in said outer layer.

The rigid interconnection between the insulating material and the inner and outer semiconducting layers should be uniform over substantially the entire interface such that no cavities, pores or similar occur. With the high voltage levels contemplated according to the invention, the electrical and thermal loads which may arise will impose extreme demands on the insulation material. It is known that so-called partial discharges, PD, generally constitute a serious problem for the insulating material in high-voltage installations. If cavities, pores or the like arise, internal corona discharges may arise at high electric voltages, whereby the insulating material is gradually degraded and the result could be electric breakdown through the insulation. This may lead to serious breakdown of the electromagnetic device. Thus, the insulation should be homogenous.

The inner layer inwardly of the insulation should have an electrical conductivity which is lower than that of the electrical conductor but sufficient for the inner layer to function equalizing with regard to potential and, accordingly, equalizing with respect to the electrical field externally of the inner layer. This in combination with the rigid interconnection of the inner layer and the electrical insulation over substantially the entire interface, i.e. the absence of cavities etc, means a substantially uniform electrical field externally of the inner layer and a minimum of risk for PD.

It is preferred that the inner layer and the solid electrical insulation are formed by materials having substantially equal thermal coefficients of expansion. The same is preferred as far as the outer layer and the solid insulation are concerned. This means that the inner and outer layers and the solid electrical insulation will form an insulation system which on temperature changes

expands and contracts uniformly as a monolithic part without those temperature changes giving rise to any destruction or disintegration in the interfaces. Thus, intimacy in the contact surface between the inner and outer layers and the solid insulation is ensured and conditions are created to maintain this intimacy during prolonged operation periods. The adherence should be of such a nature that adherence between at least the inner layer and the solid insulation and preferably also the outer layer and the solid insulation is ensured also in connection with such bending that the electric conductor and the insulation system will be subjected to. It is pointed out here that the cable, in order to be able to carry out threading of the winding, should be bendable or flexible in a radius of curvature which is less than 25 times the cable diameter, preferably less than 15 times the cable diameter. The most preferred is that the cable is flexible down to a radius of curvature which is less than or substantially similar to 8 times the cable diameter.

It is essential that the insulation system consists of materials having a good elasticity. The E-modulus of the materials should be comparatively low, i.e. the resistance to deformation of the material should be relatively low. In order to avoid that hazardous shear tensions occur in the border zone between different layers contained in the insulation system, it is preferred that the electricity (E-modulus) of the layers contained in the insulation system is substantially equal.

The electrical load on the insulation system decreases as a consequence of the fact that the inner and the outer layers of semiconducting material around the insulation will tend to form substantially equipotential surfaces and in this way the electrical field in the insulation properly will be distributed relatively uniformly over the thickness of the insulation.

It is known, per se, in connection with transmission cables for high-voltage and for transmission of electric energy, to design conductors with an insulation of a solid insulation material with inner and outer layers of semiconducting material. In transmission of electric energy, it has since long been realised that the insulation should be free from defects. However, in high voltage cables for transmission, the electric potential does not change along the length of the cable but the potential is basically at the same level. However, also in high voltage cables for transmission purposes, instantaneous potential differences may occur due to transient occurrences, such as lightning. According to the present invention a flexible cable according to the enclosed claims is used as a winding in the electromagnetic device.

An additional improvement may be achieved by constructing the electric conductor in the winding from smaller, so-called strands, at least some of which are insulated from each other. By making these strands to have a relatively small cross section, preferably approximately circular, the magnetic field across the strands will exhibit a constant geometry in relation to the field and the occurrence of eddy currents are minimized.

According to the invention, the winding is thus preferably made in the form of a cable comprising the electric conductor and the previously described insulation system, the inner layer of which extends about the strands of the conductor. Outside of this inner semiconducting layer is the main insulation of the cable in the form of a solid insulation material.

The outer semiconducting layer shall according to the invention exhibit such electrical properties that a potential equalization along the conductor is ensured. The outer layer may, however, not exhibit such conductivity properties that an induced current will flow along the surface, which could cause losses which in turn may create an unwanted thermal load. For the inner and

outer layers the resistance statements (at 20°C) defined in the enclosed claims 22 and 23 are valid. With respect to the inner semiconducting layer, it must have a sufficient electrical conductivity to ensure potential equalization for the electrical field but at the same time this layer must have such a resistivity that the enclosing of the electric field is ensured.

It is important that the inner layer equalizes irregularities in the surface of the conductor and forms an equipotential surface with a high surface finish at the interface with the solid insulation. The inner layer may be formed with a varying thickness but to ensure an even surface with respect to the conductor and the solid insulation, the thickness is suitably between 0.5 and 1 mm.

Such a flexible winding cable which is used according to the invention in the electromagnetic device thereof is an improvement of a XLPE (cross-linked poly ethylene) cable or a cable with EP (ethylene-propylene) rubber insulation. The improvement comprises, inter alia, a new design both as regards the strands of the conductor and in that the cable, at least in some embodiments, has no outer casing for mechanical protection of the cable. However, it is possible according to the invention to arrange a conducting metal shield and an outer mantle externally of the outer semiconducting layer. The metal shield will then have the character of an outer mechanical and electrical protection, for instance to lightning. It is preferred that the inner semiconducting layer will lie on the potential of the electrical conductor. For this purpose at least one of the strands of the electrical conductor will be uninsulated and arranged so that a good electrical contact is obtained to the inner semiconducting layer. Alternatively, different strands may be alternatingly brought into electrical contact with the inner semiconducting layer.

Manufacturing transformer or reactor windings of a cable according to the above entails drastic differences as regards the electric field distribution between conventional power transformers/reactors and a power transformer/reactor according to the invention. The decisive advantage with a cable-formed winding according to the invention is that the electric field is enclosed in the winding and that there is thus no electric field outside the outer semiconducting layer. The electric field achieved by the current-carrying conductor occurs only in the solid main insulation. Both from the design point of view and the manufacturing point of view this means considerable advantages:

- the windings of the transformer may be formed without having to consider any electric field distribution and the transposition of strands, mentioned under the background art, is omitted;

- the core design of the transformer may be formed without having to consider any electric field distribution;

- no oil is needed for electrical insulation of the winding, that is, the medium surrounding the winding may be air;

- no special connections are required for electrical connection between the outer connections of the transformer and the immediately connected coils/windings, since the electrical connection, contrary to conventional plants, is integrated with the winding;

- the manufacturing and testing technology which is needed for a power transformer according to the invention is considerably simpler than for a conventional power transformer/reactor since the impregnation, drying and vacuum treatments described under the description of the background art are not needed.

In application of the invention as a rotating electric machine a substantially reduced thermal load on the stator is obtained.

Temporary overloads of the machine will, thus, be less critical and it will be possible to drive the machine at overload for a longer period of time without running the risk of damage arising. This means considerable advantages for owners of power generating plants who are forced today, in case of operational disturbances, to rapidly switch to other equipment in order to ensure the delivery requirements laid down by law.

With a rotating electric machine according to the invention, the maintenance costs can be significantly reduced because transformers and circuit breakers do not have to be included in the system for connecting the machine to the power network.

Above it has already been described that the outer semiconducting layer of the winding cable is intended to be connected to ground potential. The purpose is that the layer should be kept substantially on ground potential along the entire length of the winding cable. It is possible to divide the outer semiconducting layer by cutting the same into a number of parts distributed along the length of the winding cable, each individual layer part being connectable directly to ground potential. In this way a better uniformity along the length of the winding cable is achieved.

Above it has been mentioned that the solid insulation and the inner and outer layers may be achieved by, for instance, extrusion. Other techniques are, however, also well possible, for instance formation of these inner and outer layers and the insulation respectively by means of spraying of the material in question onto the conductor/winding.

It is preferred that the winding cable is designed with a circular cross section. However, also other cross sections may be used in cases where it is desired to achieve a better packing density.

To build up a voltage in the rotating electric machine, the cable is disposed in several consecutive turns in slots in the magnetic core. The winding can be designed as a multi-layer concentric cable winding to reduce the number of coil-end crossings. The cable may be made with tapered insulation to utilize the magnetic core in a better way, in which case the shape of the slots may be adapted to the tapered insulation of the winding.

A significant advantage with a rotating electric machine according to the invention is that the E field is near zero in the coil-end region outside the outer semiconductor and that with the outer casing at ground potential, the electric field need not be controlled. This means that no field concentrations can be obtained, neither within sheets, in coil-end regions nor in the transition therebetween.

In a method for manufacturing a device according to the invention, a flexible cable, which is threaded into openings in slots in a magnetic core of the rotating electrical machine, is used as a winding. Since the cable is flexible, it can be bent and this permits a cable length to be disposed in several turns in a coil. The coil ends will then consist of bending zones in the cables. The cable may also be joined in such a way that its properties remain constant over the cable length. This method entails considerable simplifications compared with the state of the art. The so-called Roebel bars are not flexible but must be preformed into the desired shape. Winding of insulation and impregnation of the coils is also an exceedingly complicated and expensive technique when manufacturing rotating electric machines today.

To sum up, thus, an electromagnetic device in the form of a rotating electric machine according to the invention means a considerable number of important advantages in relation to corresponding prior art machines. First of all, the machine according to the invention can be connected directly to a power

network at all types of high voltage. Another important advantage is that ground potential has been consistently conducted along at least a part of and preferably along the whole winding, which means that the coil-end region can be made compact and that bracing means at the coil-end region can be applied at practically ground potential. Still another important advantage is that oil-based insulation and cooling systems disappear also in rotating electric machines as already has been pointed out above with regard to power transformers/reactors. This means that no sealing problems may arise and that the dielectric ring previously mentioned is not needed. Important is also that all forced cooling can be made at ground potential.

BRIEF DESCRIPTION OF THE DRAWINGS

With reference to the enclosed drawings, a more specific description of embodiment examples of the invention will follow hereinafter.

In the drawings:

Fig 1	is a diagrammatical view illustrating the device according to the invention in the form of a transformer;
Fig 2	is a diagrammatical view of a transformer variant;
Fig 3	is a diagrammatical view of a further transformer variant;
Fig 4	is a view of an embodiment similar to the one in Fig 3 but concerns a reactor;
Fig 5	is a diagrammatical view illustrating a generator embodiment;
Fig 6	is a partly cut view showing the parts included in the current modified standard cable;
Fig 7	is an axial end view of a sector/pole pitch of a magnetic circuit according to the invention;

Fig 8 is a view showing the electric field distribution around a winding of a conventional power transformer/reactor;

Fig 9 is a perspective view showing an embodiment of a power transformer according to the invention;

Fig 10 is a cross section illustrating a cable structure modified relative to Fig 1 and having several electrical conductors; and

Fig 11 is a cross section of a further cable structure comprising several electric conductors but in another arrangement than that in Fig 10.

DESCRIPTION OF PREFERRED EMBODIMENTS

The electromagnetic device illustrated in Fig 1 has the nature of a transformer. It comprises a magnetic circuit 1 and two electric circuits 2, 3, each comprising at least one coil shaped winding 4 and 5 respectively.

It is illustrated in the example that the transformer comprises a core 6 of a magnetic material. The core consists suitably of a package of magnetic sheets to reduce eddy-current losses. However, it is pointed out that it is not a prerequisite for application of the invention that a core is really present. Air wound embodiments etc are, thus, well possible within the scope of the invention. It follows from this that the term magnetic circuit is to be interpreted in a wide sense. The term in question means, accordingly, not more than that the magnetic field generated by the windings 4, 5 occurring should be capable of generating a magnetic flux.

The device according to the invention comprises an arrangement generally denoted 7 to control operation of the transformer. This control arrangement 7 is adapted to control frequency, amplitude and/or phase as concerns electric power exiting the transformer.

In the example the electric circuit 2 forms the primary side of the transformer whereas the electric circuit 3 forms the secondary side of the transformer. Power from the device exits, accordingly, via the secondary circuit 3, to which a load diagrammatically indicated with 8 is coupled. This load may be of an arbitrary nature, e.g. consumers proper but also distribution and transmission networks.

The control arrangement 7 comprises means 9 for controlling the magnetic flux in the magnetic circuit 1. The control means 9 includes, in the example, at least one control winding inductively connected to the magnetic circuit 1. In the example this control winding 9 is wound about a portion of the core 6. In a coreless transformer embodiment the control winding 9 must be co-ordinated such with the primary and secondary windings 4 and 5 respectively that the magnetic flux induced in the coreless magnetic circuit is inductively coupled to the control winding 9.

The control arrangement 7 is, according to a preferred embodiment of the invention, conceived to be of an active type, i.e. the control arrangement 7 should be adapted to actively control, via the control winding 9, the magnetic flux in the magnetic circuit 9 to obtain the desired character. It is then preferred that the control arrangement 7 comprises an external power source such that the control arrangement 7 is capable of controlling the magnetic flux through the magnetic circuit 1 by causing a current to flow through the winding 9. The invention is particularly preferable in connection with high voltage applications. This means, accordingly, that a comparatively high voltage is normally intended to be associated to the electric circuits 2 and 3. In such a case, it is, however, sufficient for control purposes that the control arrangement 7 causes a relatively high current to flow in the winding 9 with a relatively low voltage. The control arrangement 7 may be adapted to, for control purposes, add a magnetic flux addition to the magnetic flux in the magnetic circuit 1. This flux

addition will be added to the flux otherwise occurring and by suitable control of this flux addition, the desired parameters with regard to the power exiting through the secondary circuit 3 may be achieved. The arrangement 7 may be adapted to receive, as basis for its control function, voltage information from a voltage measuring device 10 with respect to the voltage in the secondary circuit and/or over the load 8. A current measuring member 11 serves for current measurement in the secondary circuit 3. The flux addition generated via the control arrangement 7 may, as mentioned before, be used to control frequency, amplitude and/or phase as concerns the power exiting via the secondary circuit 3.

It is pointed out that the control arrangement 7 may be adapted to obtain external control instructions via an input 12.

Furthermore, it is pointed out that the control arrangement 7 may be adapted to effect a passive control via the control winding 9. A passive control in this regard means that power from some external source is not used for control. In this connection it is pointed out that the control arrangement 7 may be capable of coupling one or more passive elements, such as resistors, capacitors or inductances coupled in series or parallel, over the control winding 9. Such passive elements coupled to the control winding 9 in a manner adapted to the purpose enable, accordingly, different influences on the magnetic flux, said influences in their turn resulting in consequences with respect to frequency, amplitude and/or phase as concerns the electric power from the device.

It also appears from Fig 1 that the device on its primary side comprises a voltage measuring device 13 and a current measuring device 14 similar to what is occurring on the secondary side.

Fig 2 illustrates a transformer embodiment differing from the one just described in Fig 1 only in the regard that the magnetic circuit 1 here comprises a core 6 comprising a further leg 16 in addition to the one occurring on the secondary side in Fig 1 and denoted 15 and the one occurring on the primary side and denoted 17. Thus, this means that the core 6 according to Fig 2 will form two different flux paths diagrammatically indicated with 18 and 19 respectively. The control winding 9a is arranged in this case around the central leg 16, i.e. at the flux path 18, which passes the primary winding 4 of the transformer. The second flux path 19, on the contrary, passes around the control winding 9a via the secondary winding 5. It is now possible via the control arrangement 7, to affect the magnetic flux in the leg 16 by means of the control winding 9a, which in its turn will affect the magnetic flux in the leg 15 through the winding 5 of the secondary side. Expressed in other words, the control winding 9a is here only associated to one of the two flux paths.

The variant in Fig 3 means addition of a further control winding 9b2 to the one already occurring 9b1. These two control windings are arranged around its own of the legs 16b, 15b, i.e. these control windings 9b1 and 9b2 will belong to its own of the flux paths 18, 19. The control arrangement 7b comprises a control unit 20, which in its turn controls control elements 21 and 22 respectively coordinated with the control windings 9b1 and 9b2 respectively. By actively or passively controlling the control elements 21, 22 via the control unit 20, an adjustment may be made so that the magnetic flux either passes through only one of the flux paths 18, 19 or is divided on the same.

In connection with Fig 3 it should also be mentioned that the secondary winding 4b of the transformer comprises at least two winding parts 23 and 24 respectively coupled in series. The magnetic flux in both flux paths 18, 19 passes through the main winding part 23 whereas only the flux in the flux path 19 passes

through the winding part 24. Thus, this means that when the magnetic flux is allowed to pass only through the leg 16b by means of the control windings 9b1 and 9b2, no magnetic flux passes through the winding part 24. Thus, this means lower output voltage than that which is due for the operation case where the magnetic flux passes entirely through the flux path 19 than when the total magnetic flux passes through both secondary winding parts 23 and 24. Thus, the control winding 9b1 is intended, in such an operation case, to have interrupted magnetic flux through the leg 16b entirely or at least partially.

Fig 4 illustrates a reactor embodiment somewhat reminding of the transformer according to Fig 3. The difference consists in that the reactor does not have any secondary side so that instead its power winding is divided into two winding parts 25, 26. As in the preceding embodiment, there are two control windings 9c1 and 9c2, by means of which the magnetic flux may be controlled so that it passes through the winding part 26 in a desired degree. The entire flux always passes through the winding part 25.

Fig 5 illustrates a very simplified generator embodiment, the rotor of which is denoted 26. This rotor is in the example conceived to be a permanent magnet rotor. It would, however, also be possible to design the rotor with field windings. The magnetic circuit 1d comprises here an electric output circuit 5d inductively coupled to the magnetic flux in the core 6d. The core 6d has portions located adjacent to the rotor 26 such that the permanent magnets will generate a magnetic flux in the core during rotation of the rotor. This flux passes through the output winding 5d and generates an output effect therein. The control arrangement 7d comprises as before a control winding 9d inductively coupled to the magnetic circuit 1d. Measuring devices 10d and 11d respectively for voltage and current occur also here to supervise the output power. By means of the control arrangement

7d the control winding 9d may now be subjected to a functionality, required for the control purpose, passively or actively, for imparting the output power from the generator desired properties with regard to frequency, amplitude and/or phase.

It is pointed out that very simplified embodiments are presented in the figures and this more specifically only with one phase. In reality the embodiments may be much more complicated, in particular multiphase embodiments. The number of windings and winding parts may be much higher than what has been discussed, not only as far as the primary and secondary windings are concerned but also with respect to the number of control windings. Also the magnetic circuits may have a varying design depending upon functional requirements.

It is particularly pointed out that the circumstance that according to the invention at least one of the occurring windings comprises an electric conductor surrounded by two mutually spaced equipotential layers and a solid insulation placed between these layers means that the electric field around the conductor will be substantially enclosed in the cable such that the primary and secondary windings may be placed anywhere on the magnetic circuit with a very great freedom. Even interposition of the windings is possible. It is in this connection pointed out that the control arrangement is useful for transformers both of the type with a core and a shell.

In particular in high voltage applications the just described design of the winding is suitable. It is pointed out that normally the control winding/control windings 9 will be at a lower potential than the power windings, for what reason the control winding/control windings do not necessarily have to be provided with such an insulation system as at least one of the power windings.

An important aspect for being able to provide an electromagnetic device in accordance with the invention, is to use for at least one of the winding a conductor cable with a solid electrical insulation with an inner semiconducting layer or casing between the insulation and one or more electrical conductors located inwardly thereof and with an outer semiconducting layer or casing located outwardly of the insulation. Such cables are available as standard cables for other power engineering fields of use, namely power transmission. To be able to describe an embodiment, initially a short description of a standard cable will be made. The inner current-carrying conductor comprises a number of strands. Around the strands there is a semiconducting inner layer or casing. Around this semiconducting inner layer, there is an insulating layer of solid insulation. The solid insulation is formed by a polymeric material with low electrical losses and a high breakthrough strength. As concrete examples polyethylene (PE) and then particularly cross-linked polyethylene (XLPE) and ethylene-propylene (EP) may be mentioned. Around the outer semiconducting layer a metal shield and an outer insulation casing may be provided. The semiconducting layers consist of a polymeric material, for example ethylene-copolymer, with an electrically conducting constituent, e. g. conductive soot or carbon black. Such a cable will be referred to hereunder as a power cable.

A preferred embodiment of a cable intended for a winding in a rotating electrical machine appears from Fig 6. The cable 41 is described in the figure as comprising a current-carrying conductor 42 which comprises transposed both non-insulated and insulated strands. Electromechanically transposed, solidly insulated strands are also possible. These strands may be stranded/transposed in a plurality of layers. Around the conductor there is an inner semiconducting layer 43 which, in turn, is surrounded by a homogenous layer of a solid insulation material. The insulation 44 is entirely without insulation material of liquid

or gaseous type. This layer 44 is surrounded by an outer semiconducting layer 45. The cable used as a winding in the preferred embodiment may be provided with metal shield and external sheath but must not be so. To avoid induced currents and losses associated therewith in the outer semiconducting layer 45, this is cut off, preferably in the coil end, that is, in the transitions from the sheet stack to the end windings. The cut-off is carried such that the outer semiconducting layer 45 will be divided into several parts distributed along the cable and being electrically entirely or partly separated from each other. Each cut-off part is then connected to ground, whereby the outer semiconducting layer 45 will be maintained at, or near, ground potential in the whole cable length. This means that, around the solidly insulated winding at the coil ends, the contactable surfaces, and the surfaces which are dirty after some time of use, only have negligible potentials to ground, and they also cause negligible electric fields.

To optimize a rotating electric machine, the design of the magnetic circuit as regards the slots and the teeth, respectively, are of decisive importance. As mentioned above, the slots should connect as closely as possible to the casing of the coil sides. It is also desirable that the teeth at each radial level are as wide as possible. This is important to minimize the losses, the magnetization requirement, etc., of the machine.

With access to a conductor for the winding such as for example, the cable described above, there are great possibilities of being able to optimize the magnetic core from several points of view. In the following, a magnetic circuit in the stator of the rotating electric machine is referred to. Figure 7 shows an embodiment of an axial end view of a sector/pole pitch 46 of a machine according to the invention. The rotor with the rotor pole is designated 47. In conventional manner, the stator is composed of a laminated core of electric sheets successively composed of

sector-shaped sheets. From a back portion 48 of the core, located at the radially outermost end, a number of teeth 49 extend radially inwards towards the rotor. Between the teeth there are a corresponding number of slots 50. The use of cables 51 according to the above among other things permits the depth of the slots for high-voltage machines to be made larger than what is possible according to the state of the art. The slots have a cross section tapering towards the rotor since the need of cable insulation becomes lower for each winding layer towards the rotor. As is clear from the figure, the slot substantially consists of a circular cross section 52 around each layer of the winding with narrower waist portions 53 between the layers. With some justification, such a slot cross section may be referred to as a "cycle chain slot". Since there will be required, in such a high voltage machine, a relatively large number of layers and the availability of cables in relevant dimensions and having relevant insulation and external semiconductors is restricted it may in practice be difficult to achieve a desired continuous tapering of the cable insulation and the stator slot respectively. In the embodiment shown in Figure 7, cables with three different dimensions of the cable insulation are used, arranged in three correspondingly dimensioned sections 54, 55 and 56, that is, in practice a modified cycle chain slot will be obtained. The figure also shows that the stator tooth 49 can be shaped with a practically constant radial width along the depth of the whole slot.

It is again pointed out that the winding sections denoted 54, 55 and 56 in Fig 7 correspond to the winding denoted 5d in Fig 5. In Fig 7 on the contrary, one or more windings corresponding to the control winding 9 in Fig 5 are denoted with the reference 40. These control windings 40 are in the embodiment located radially outermost from the rotor. It is pointed out that it is not necessary to locate the control winding 9 on the location denoted 40 in Fig 7.

In an alternative embodiment, the cable which is used as a winding may be a conventional power cable as the one described above. The grounding of the outer semiconducting layer 45 then takes place by stripping the metal shield and the sheath of the cable at suitable locations.

The scope of the invention accommodates a large number of alternative embodiments, depending on the available cable dimensions as far as insulation and the outer semiconductor layer etc. are concerned. Also embodiments with so-called cycle chain slots can be modified in excess of what has been described here.

As mentioned above, the magnetic circuit may be located in the stator and/or the rotor of the rotating electric machine. However, the design of the magnetic circuit will largely correspond to the above description independently of whether the magnetic circuit is located in the stator and/or the rotor.

As winding, a winding is preferably used which may be described as a multilayer, concentric cable winding. Such a winding means that the number of crossings at the coil ends has been minimized by placing all the coils within the same group radially outside one another. This also permits a simpler method for the manufacture and the threading of the stator winding in the different slots. Since the cable used according to the invention is relatively easily flexible, the winding may be obtained by a comparatively simple threading operation, in which the flexible cable is threaded into the openings 52 present in the slots 50.

Figure 8 shows a simplified and fundamental view of the electric field distribution around a winding of a conventional power transformer/reactor, where 57 is a winding and 58 a core and 59 illustrates equipotential lines, that is, lines where the electric

field has the same magnitude. The lower part of the winding is assumed to be at ground potential.

The potential distribution determines the composition of the insulation system since it is necessary to have sufficient insulation both between adjacent turns of the winding and between each turn and ground. The figure thus shows that the upper part of the winding is subjected to the highest insulation loads. The design and location of a winding relative to the core are in this way determined substantially by the electric field distribution in the core window.

The cable which can be used in the windings contained in the dry power transformers/reactors according to the invention have been described with assistance of Fig 1. The cable may, as stated before, be provided with other, additional outer layers for special purposes, for instance to prevent excessive electrical strains on other areas of the transformer/reactor. From the point of view of geometrical dimension, the cables in question will have a conductor area which is between 2 and 3000 mm^2 and an outer cable diameter which is between 20 and 250 mm.

The windings of a power transformer/reactor manufactured from the cable described under the summary of the invention may be used both for single-phase, three-phase and polyphase transformers/reactors independently of how the core is shaped. One embodiment is shown in Figure 8 which shows a three-phase laminated core transformer. The core comprises, in conventional manner, three core limbs 60, 61 and 62 and the retaining yokes 63 and 64. In the embodiment shown, both the core limbs and the yokes have a tapering cross section.

Concentrically around the core limbs, the windings formed with the cable are disposed. As is clear, the embodiment shown in Figure 9 has three concentric winding turns 65, 66 and 67. The

innermost winding turn 65 may represent the primary winding and the other two winding turns 63 and 64 may represent secondary windings. In order not to overload the figure with too many details, the connections of the windings are not shown. Otherwise the figure shows that, in the embodiment shown, spacing bars 68 and 69 with several different functions are disposed at certain points around the windings. The spacing bars may be formed of insulating material intended to provide a certain space between the concentric winding turns for cooling, bracing, etc. They may also be formed of electrically conducting material in order to form part of the grounding system of the windings.

No control windings 9 are drawn in Fig 9.

Alternative cable designs

In the cable variant illustrated in Fig 10, the same reference characters as before are used, only with the addition of the letter a characteristic for the embodiment. In this embodiment the cable comprises several electric conductors 42a, which are mutually separated by means of insulation 44a. Expressed in other words, the insulation 44a serves both for insulation between individual adjacent electrical conductors 42a and between the same and the surrounding. The different electrical conductors 42a may be disposed in different manners, which may provide for varying cross-sectional shapes of the cable in its entirety. In the embodiment according to Fig 10 it is illustrated that the conductors 42a are disposed on a straight line, which involves a relatively flat cross-sectional shape of the cable. From this it can be concluded that the cross-sectional shape of the cable may vary within wide limits.

In Fig 10 there is supposed to exist, between adjacent electrical conductors, a voltage smaller than phase voltage. More specifically, the electrical conductors 42a in Fig 10 are supposed to be

formed by different revolutions in the winding, which means that the voltage between these adjacent conductors is comparatively low.

As before, there is a semiconducting outer layer 45a exteriorly of the insulation 44a obtained by a solid electrical insulation material. An inner layer 43a of a semiconducting material is arranged about each of said electrical conductors 42a, i.e. each of these conductors has a surrounding inner semiconducting layer 43a of its own. This layer 43a will, accordingly, serve potential equalizing as far as the individual electrical conductor is concerned.

The variant in Fig 11 uses the same reference characters as before only with addition of the letter b specific for the embodiment. Also in this case there are several, more specifically three, electrical conductors 42b. Phase voltage is supposed to be present between these conductors, i.e. a substantially higher voltage than the one occurring between conductors 42a in the embodiment according to Fig 10. In Fig 11 there is an inner semiconducting layer 43b inwardly of which the electrical conductors 42b are arranged. Each of the electrical conductors 42b is, however, enclosed by a further layer 70 of its own, with properties corresponding to the properties discussed hereinabove with regard to the inner layer 43b. Between each further layer 70 and the layer 43b arranged thereabout, there is insulation material. Accordingly, the layer 43b will occur as a potential equalizing layer outside the further layers 60 of semiconducting material belonging to the electrical conductors, said further layers 70 being connected to the respective electrical conductor 42b to be placed on the same potential as the conductor.

Possible modifications

It is evident that the invention is not only limited to the embodiments discussed above. Thus, the man skilled within this art will

realise that a number of detailed modifications are possible when the basic concept of the invention has been presented without deviating from this concept as it is defined in the enclosed claims. As an example, it is pointed out that the invention is not only restricted to the specific material selections exemplified above. Functionally equal materials may, accordingly, be used instead. As far as the manufacturing of the insulation system according to the invention is concerned, it is pointed out that also other techniques than extrusion and spraying are possible as long as intimacy between the various layers is achieved. Furthermore, it is pointed out that additional equipotential layers could be arranged. For example, one or more equipotential layers of semiconducting material could be placed in the insulation between those layers designated as "inner" and "outer" hereinabove. It is again pointed out that it is normally not supposed to be necessary according to the invention to form the control windings 9 by means of such a flexible cable as the one discussed hereinabove as a consequence of the fact that the control winding or control windings are normally at a lower voltage than the rest of the windings of the electromagnetic device in question. More specifically, the rest of the windings may be true high voltage windings. For the rest it is pointed out that the exact control principle on execution of the method according to the invention may be varied in a variety of ways within the scope of control functions aimed at.